



Climate Change Impacts in the Great Lakes

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Summary

Global climate change is altering the climate and ecosystems of the Laurentian Great Lakes of North America. Published scientific research shows that air and water temperatures are increasing, ice is freezing later in the winter and melting earlier in the spring, ranges of tree species are shifting north, and cool water fish species are declining in some areas.

The following tables and maps summarize information on observed and projected climate change and resource impacts in the Great Lakes region. This scientific information can help resource managers as they develop adaptation measures to increase the resilience of resources to climate change. The material was compiled to prepare participants in the National Park Service Climate Change Scenario Planning training in Duluth, Minnesota, USA, October 5-7, 2010.

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			Projected 21 st Century Change		
Climate or Physical Variable	Trend	Observed 20 th Century Change	Medium Emissions Scenario (IPCC A1B or B2)	Warmer Emissions Scenario (IPCC A1FI or A2)	Confidence in Scientific Understanding (IPCC Terms)
Temperature	↑	Great Lakes Basin: $+0.9 \pm 0.2^{\circ}\text{C}$ (Gonzalez et al. 2010, IPCC 2007)	Great Lakes Basin: $+4.0 \pm 0.8^{\circ}\text{C}$ (Gonzalez et al. 2010, IPCC 2007), summer increases greater than winter increases (Hayhoe et al. 2010)	Great Lakes Basin: $+4.4 \pm 0.8^{\circ}\text{C}$ (Gonzalez et al. 2010, IPCC 2007), summer increases greater than winter increases (Hayhoe et al. 2010)	Very High (IPCC 2007)
Precipitation	↑	Great Lakes Basin: $+19 \pm 7\%$ (Gonzalez et al. 2010, IPCC 2007), increase in the fall greater than in other seasons (Small et al. 2006)	Great Lakes Basin: $+6 \pm 4\%$ (Gonzalez et al. 2010, IPCC 2007), summer decreases and winter increases (Hayhoe et al. 2010)	Great Lakes Basin: $+4 \pm 3\%$ (Gonzalez et al. 2010, IPCC 2007), summer decreases and winter increases (Hayhoe et al. 2010)	High (Hayhoe et al. 2010)
Wind	↔	Lake Superior: +5% increase in wind speed above water due to disrupted boundary layer (Desai et al. 2009)	Perhaps increased frequency of high intensity winds due to increased frequency of heavy storm events or decrease in average wind speed (Sousounis and Grover 2002).	Perhaps increased frequency of high intensity winds due to increased frequency of heavy storm events or decrease in average wind speed (Sousounis and Grover 2002).	Low
Growing season length	↑	Illinois: last spring freeze one week earlier (Robeson 2002)	Great Lakes region: +1.5 to 3 standard deviations (IPCC 2007); +3 weeks (Kling et al. 2003)	Great Lakes region: +2 to 3.5 standard deviations (IPCC 2007); +6 weeks (Kling et al. 2003)	High
Extreme temperature events	↑	Great Lakes region: Frequent cold waves in 1970s and 1980s, scarcity of cold waves in 1990s (DeGaetano and Allen 2002); heat waves 1995, 1999, 2006 (Hayhoe et al. 2010)	Great Lakes region: +2.25 to 3.75 standard deviation change in heat waves (longest period in the year of ≥ 5 days with maximum temperature $\geq 5^{\circ}\text{C}$ above average) (IPCC 2007); Decrease in extremely cold days, increase in extremely hot days (Sousounis and Grover 2002)	Great Lakes region: +2.5 to 4.25 standard deviation change in heat waves (longest period in the year of ≥ 5 days with maximum temperature $\geq 5^{\circ}\text{C}$ above average) (IPCC 2007); Decrease in extremely cold days, increase in extremely hot days (Sousounis and Grover 2002)	High (IPCC 2007)

			Projected 21 st Century Change		
Climate or Physical Variable	Trend	Observed 20 th Century Change	Medium Emissions Scenario (IPCC A1B or B2)	Warmer Emissions Scenario (IPCC A1FI or A2)	Confidence in Scientific Understanding (IPCC Terms)
Extreme precipitation events	↑	Great Lakes region: Doubled frequency of heavy rain events (Kunkel et al. 1999)	Great Lakes region: +0.75 to 1.25 standard deviation change in precipitation intensity (ratio of annual precipitation to number of wet days) (IPCC 2007); Increase in events >12.5 mm (Sousounis and Grover 2002)	Great Lakes region: +0.75 to 1.5 standard deviation change in precipitation intensity (ratio of annual precipitation to number of wet days) (IPCC 2007); Increase in events >12.5 mm (Sousounis and Grover 2002); Doubling of events (Kling et al. 2003)	High (IPCC 2007)
Snowfall	↔	Great Lakes region: +2% per decade (Kunkel et al. 2009b); Lakes Superior, Michigan, Huron: significant increase in lake effect snow; Lakes Erie, Ontario: no significant change (Kunkel et al. 2009b); Ontario: significant increase (Burnett et al. 2003); shift of precipitation from rainfall to snowfall (Ellis and Johnson 2004)	Great Lakes region: Decrease in total snowfall (Cherkauer and Sinha 2010), -30 to 50% days with snow (Hayhoe et al. 2010)	Great Lakes region: Decrease in total snowfall (Cherkauer and Sinha 2010), -45 to 60% days with snow (Hayhoe et al. 2010)	Medium
Snow cover	↓	Great Lakes region: -6 to -15% change in area 1967-2004	Great Lakes region: as much as -12% change in area (IPCC 2007)	Decrease greater than IPCC emissions scenario A1B (IPCC 2007)	High (IPCC 2007)
Evaporation	↑		Great Lakes region: +0.1 to 0.2 mm d ⁻¹ (IPCC 2007); increased winter evaporation as ice cover decreases (Lofgren et al. 2002)	Increase greater than IPCC emissions scenario A1B	Medium

			Projected 21 st Century Change		
Climate or Physical Variable	Trend	Observed 20 th Century Change	Medium Emissions Scenario (IPCC A1B or B2)	Warmer Emissions Scenario (IPCC A1FI or A2)	Confidence in Scientific Understanding (IPCC Terms)
Runoff	↑	Lakes Michigan and Huron: increase in winter (Argyilan and Forman 2003); earlier dates for spring melt and peak runoff (Dyer and Mote 2006); Lakes Michigan, Huron, Erie: decrease in total runoff (Assel et al. 2004); Wisconsin, Michigan, Ohio, New York: increase in autumn and winter (Johnston and Shmagin 2008)	Lake Michigan: +7 to 20%, possible decreases in autumn (Cherkauer and Sinha 2010)	Lake Michigan: +10 to 16%, greater in winter and spring, possible decreases in autumn (Cherkauer and Sinha 2010)	High
Lake level	↔	Great Lakes: Decreasing trend since 1973 (Sellinger et al. 2008); Lake Superior: record lows at beginning and end of 1860-2007 time series (Lamon and Stow 2010); Lakes Michigan, Huron, Erie: record highs 1973, 1986, record lows 1997-2000 (Assel et al. 2004); Inter-decadal cycles could be related to North Atlantic Oscillation sea surface temperature cycles (Hanrahan et al. 2009) or sunspot cycles (Sellinger et al. 2008); Shift to earlier spring maximum and autumn minimum (Lenters 2001)	Lakes Michigan and Huron: mean -0.3 m, due to increased evaporation, but chance of a slight increase if increased precipitation exceeds evaporation losses (Angel and Kunkel 2010); Reduced ice cover could increase evaporation (Hanrahan et al. 2009); Apostle Islands NL, Indiana Dunes NL, Sleeping Bear Dunes NL: moderate vulnerability to lake level change (Pendleton et al. 2010)	Lakes Superior -0.1 m, Michigan, Huron, Ontario -0.4 m, Erie -0.2 m, due to increased evaporation, but chance of a slight increase if increased precipitation exceeds evaporation losses (Angel and Kunkel 2010); Reduced ice cover could increase evaporation (Hanrahan et al. 2009)	Medium (Angel and Kunkel 2010, Sellinger et al. 2008)

			Projected 21 st Century Change		
Climate or Physical Variable	Trend	Observed 20 th Century Change	Medium Emissions Scenario (IPCC A1B or B2)	Warmer Emissions Scenario (IPCC A1FI or A2)	Confidence in Scientific Understanding (IPCC Terms)
Lake temperatures	↑	Lakes Superior and Erie: near-shore +1°C, summer thermal stratification duration +2 weeks (McCormick and Fahnenstiel 1999); Lake Superior: open water +3.5°C, summer thermal stratification +3 weeks (Austin and Coleman 2008) due to decreased winter ice (Austin and Colman 2007), Lake Huron open water +2.9°C, Lake Erie open water no significant change, Lake Ontario +1.6°C (Dobiesz and Lester 2009)	Lakes Superior +5°C, Huron +3°C, Erie +2°C, Ontario +3°C (Trumpickas et al. 2009); increase in summer stratification (Fang and Stefan 2009)	Lakes Superior +7°C, Huron +4°C, Erie +3°C, Ontario +5°C (Trumpickas et al. 2009); increase in summer stratification (Fang and Stefan 2009)	High
Lake ice cover	↓	Great Lakes: freeze 3 days decade ⁻¹ later, breakup 2 days decade ⁻¹ earlier (Jensen et al. 2007); Lake Superior -0.04 ± 0.02 % decade ⁻¹ (Austin and Colman 2007); Lake Michigan: freeze 11 days later, breakup 11 days earlier; Lake Ontario: freeze 37 days earlier, breakup 7 days earlier (Magnusson et al. 2000); Occurrence of very densely packed ice declined ~20% near lake shores and ~30% in deeper areas, 1973-2002 (Assel 2003)	Lake Superior: 0% (current) to 4% ice-free winters, Lake Erie 2% (current) to 4% ice-free winters (Kling et al. 2003)	Lake Superior 0% (current) to 45% ice-free winters, Lake Erie 2% (current) to 96% ice-free winters (Kling et al. 2003); Lake Michigan no winter ice as early as 2020 (Hayhoe et al. 2010)	High

Resource or Process	Observed 20 th Century Change	Projected 21st Century Impacts (Generally Under Medium Emissions Scenario IPCC A1B)	Confidence in Scientific Understanding (IPCC Terms)
Terrestrial Ecosystems			
Vegetation distribution	Northward shift of conifer seedlings (Woodall et al. 2009); Northward shift of 62% of eastern North America tree species (Murphy et al. 2010); Lake-effect snow maintains mesic species (e.g. hemlock) (Henne et al. 2007)	<ul style="list-style-type: none"> • High to very high vulnerability of ecosystems to northward biome shifts of 50 to 70% of the Great Lakes basin (Gonzalez et al. 2010) • Northward shifts of boreal conifer, temperate conifer, and temperate mixed forest species (USGCRP 2000, Walker et al. 2002, Scheller and Mladenoff 2005, 2008, Gonzalez et al. 2010) • Projected northward shift of ranges of 120 species across eastern North America, with 66 spp. increasing and 54 spp. decreasing range $\geq 10\%$ (Iverson et al. 2008) • Fewer thermal refugia at Voyageurs NP (Davis et al. 2000) • Reduction of conifer species in Boundary Waters Canoe Wilderness Area (Frelich and Reich 2009) • Contraction of wetlands due to changes in timing of precipitation, runoff, and groundwater recharge • Shifting of sand dunes due to changes in winds could shift grass species (shore side) and tree species (land side) 	High
Wildfire	Fire frequency $-1 \pm 1\%$ (Gonzalez et al. 2010); Extensive fires in Ontario north of Minnesota and north of Lake Huron (Drever et al. 2008); Fire suppression has reduced densities of Pinus spp. (Frelich and Reich 2009)	<ul style="list-style-type: none"> • Fire frequency $+6 \pm 64\%$ (Gonzalez et al. 2010) 	Low
Invasive plant species		<ul style="list-style-type: none"> • Increase in garlic mustard due to increase in invasive exotic earthworms (Frelich and Reich 2009) 	Low
Mammals	Northern shift of ranges of 8 small mammal species, up to 225 km (Myers et al. 2009)	<ul style="list-style-type: none"> • The range of small mammals (e.g. Franklin's ground squirrel) may need to shift north as much as 4 km y^{-1} (Francl et al. 2010) 	Low

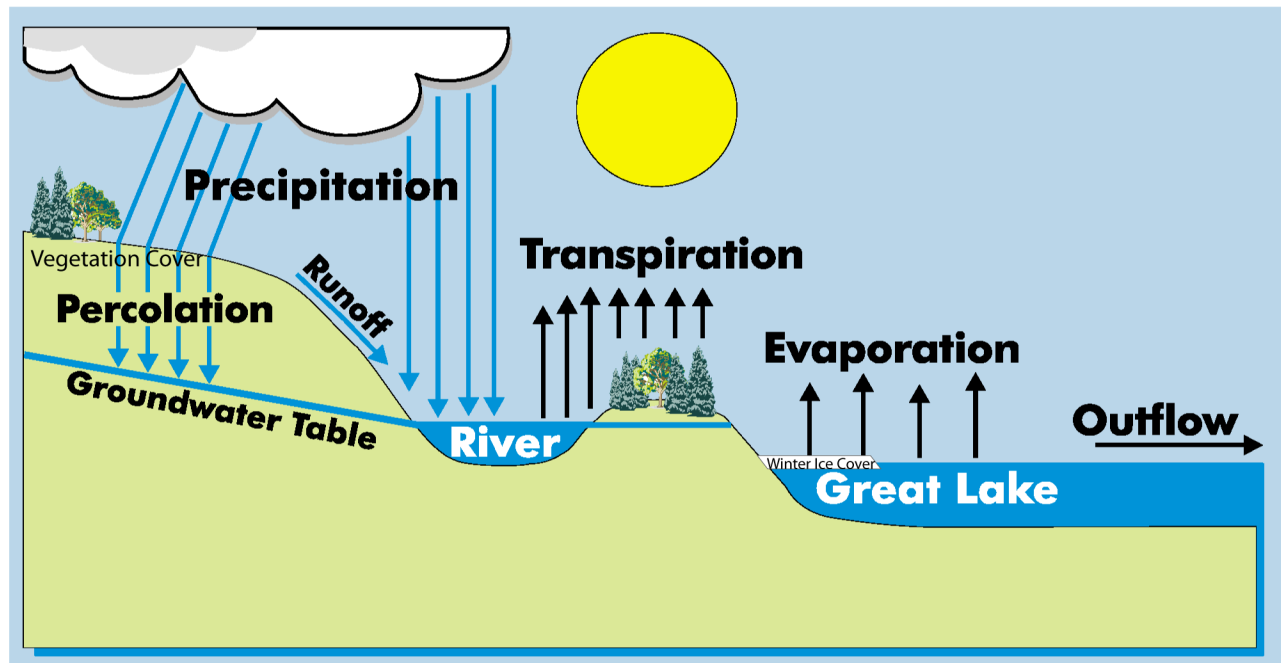
Resource or Process	Observed 20 th Century Change	Projected 21st Century Impacts (Generally Under Medium Emissions Scenario IPCC A1B)	Confidence in Scientific Understanding (IPCC Terms)
Birds	Wisconsin: 17 of 19 species showed earlier spring arrival or song, 9 of 17 were statistically significant (Bradley et al. 1999)	<ul style="list-style-type: none"> • Illinois: northward shift of ranges with 54 spp. gaining and 76 spp. losing $\geq 10\%$ (Hellman et al. 2010) (Kling et al. 2003): • Mismatch of timing of spring stopovers of long-distance migratory birds (e.g. scarlet tanagers, warblers, thrushes, flycatchers) that time migration by day length and phenology of food sources (tree parts, caterpillars), determined by climate • Earlier and more successful breeding of resident birds (cardinals, chickadees) • Competition of increased resident bird populations and migrants over food • Reduction of safe breeding sites due to changes in timing and severity of floods • Northern migratory species (e.g. Canada goose) may winter farther north • Reduced habitat for wetland birds due to reduced summer precipitation and diminished groundwater recharge 	Medium
Amphibians		<ul style="list-style-type: none"> • Reduction of safe breeding sites due to changes in timing and severity of floods (Kling et al. 2003) • Increase in ultraviolet radiation damage in clear shallow water bodies due to drought and lower water levels (Kling et al. 2003) 	Low
Insects		<ul style="list-style-type: none"> • Illinois: northward shift of ranges, with 20 spp. leaving region and 19 spp. appearing, out of 115 examined (Hellman et al. 2010) • Expansion of gypsy moth range and damage to forests (Kling et al. 2003, Hellman et al. 2010) • Increased conditions for spread of bark beetles (Hellman et al. 2010) 	Low
Aquatic ecosystems			

Resource or Process	Observed 20 th Century Change	Projected 21st Century Impacts (Generally Under Medium Emissions Scenario IPCC A1B)	Confidence in Scientific Understanding (IPCC Terms)
Shore	Recent increase of exposed shore areas (see Lake level)	<ul style="list-style-type: none"> • More model runs project increased exposure of shore areas than project inundation or flooding (see Lake level) 	Medium
Coastal erosion		<ul style="list-style-type: none"> • Coastal change potential (% of coast line): Apostle Islands NL: very high 21%, high 30%; Indiana Dunes NL: very high 20%, high 23%; Sleeping Bear Dunes NL: very high 14%, high 40% (Pendleton et al. 2007, 2010) • Increases in extreme storm events could increase coastal erosion • Decreased lake levels and decreased ice shear could decrease coastal erosion 	Medium
Sand dunes		<ul style="list-style-type: none"> • Increasing winds could shift dunes • No change otherwise 	Very low
Primary production		<ul style="list-style-type: none"> • Reduction due to increased summer stratification (Brooks and Zastrow 2002) 	Medium

Resource or Process	Observed 20 th Century Change	Projected 21st Century Impacts (Generally Under Medium Emissions Scenario IPCC A1B)	Confidence in Scientific Understanding (IPCC Terms)
Fish		<ul style="list-style-type: none"> • Declines in cold-water species (e.g. lake trout, brook trout, whitefish) and cool-water species (e.g. muskie, walleye) in favor of warm-water species (e.g. smallmouth bass, bluegill) (USGCRP 2000, Kling et al. 2003) • Increased frequency of fish kills caused by hypoxia and anoxia due to increased duration of summer stratification and oxygen depletion by decomposition of organic matter (USGCRP 2000, Kling et al. 2003) • Minnesota lakes: Walleye spawning occurring earlier as the date of ice free conditions moves earlier (Schneider et al. 2010) • Northward (horizontal) or downward (vertical) shift of species ranges, depending on dispersal capabilities and connections of water courses (USGCRP 2000, Kling et al. 2003, Hellman et al. 2010) • Reduced lake whitefish recruitment due to lower egg survival under warmer temperatures and reduced ice cover, which protects eggs from winter storm disturbances (Brown et al. 1993) • Ontario lakes: 20% vulnerable to invasion of smallmouth bass, displacing native lake trout (Sharma et al. 2009) • Potential high vulnerability of small, shallow, and isolated lakes to loss of cool-water species • Potential refugia in Lake Superior, the deepest Great Lake, for whitefish and lake trout • Less winter kill in shallow lakes • Secondary changes in food webs 	High
Invasive aquatic species		<ul style="list-style-type: none"> • Continued increases in zebra mussel, carp 	Medium
Cultural Resources			
Sacred sites of Indian and First Nations		<ul style="list-style-type: none"> • Inundation or exposure of lake shore sites • Alteration of vegetation at upland sites 	Very low

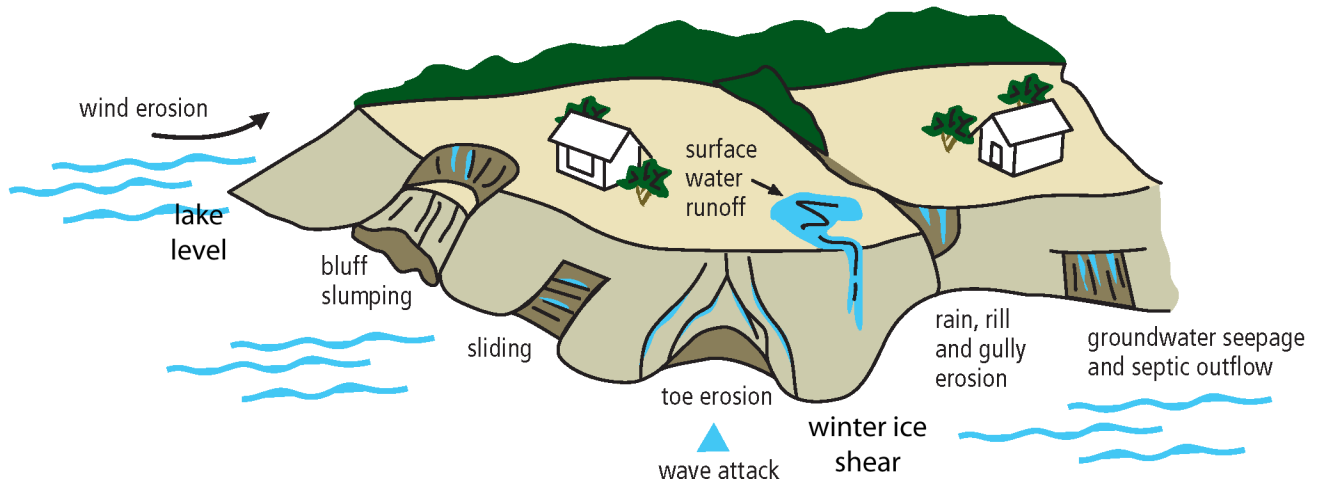
Resource or Process	Observed 20 th Century Change	Projected 21st Century Impacts (Generally Under Medium Emissions Scenario IPCC A1B)	Confidence in Scientific Understanding (IPCC Terms)
Natural resource use by Indian and First Nations		<ul style="list-style-type: none"> • Changes in fish harvest • Potential reductions in wild rice harvest due to changes in precipitation, runoff, and extent of wetlands • Reduced availability of paper birch for canoes and other items 	Medium
Historical buildings		<ul style="list-style-type: none"> • Changes in outdoor structures due to changes in ozone and other air pollutants 	Very low
Visitor experiences		<ul style="list-style-type: none"> • Decline in ice and snow-related activities (USGCRP 2000, Kling et al. 2003); Changes in length of summer or winter outdoor activity seasons • Changes in interpretation of natural history as climate change alters species and ecosystems • Changes in interpretation of Indian or First Nation activities discontinued due to climate impacts 	Medium
Sport fishing		<ul style="list-style-type: none"> • Reduction of popular cool-water species (e.g. muskie and walleye) (USGCRP 2000, Kling et al. 2003) 	Medium
Infrastructure			
Docks for small water craft	Vertical rub rails installed at Apostle Islands NL due to fall in level of Lake Superior	<ul style="list-style-type: none"> • Rebuilding or repositioning if lake levels rise or fall (USGCRP 2000, Kling et al. 2003) 	Medium
Shipping ports		<ul style="list-style-type: none"> • Re-engineering required if lake levels fall or rise substantially 	Low

Factors Influencing Water Levels in the Great Lakes



Original diagram from the U.S. Army Corps of Engineers, with modifications

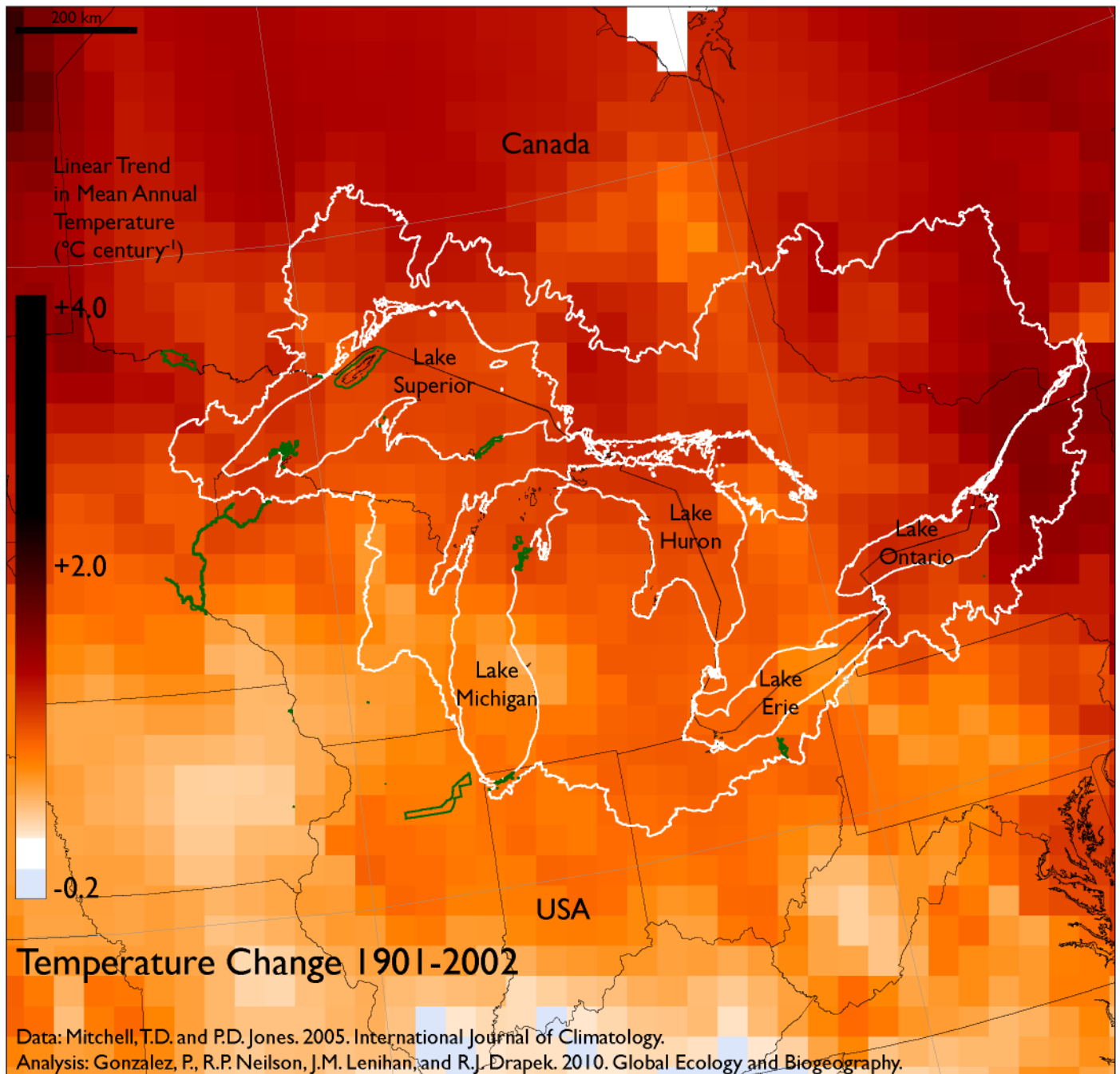
Factors Influencing Coastal Erosion in the Great Lakes

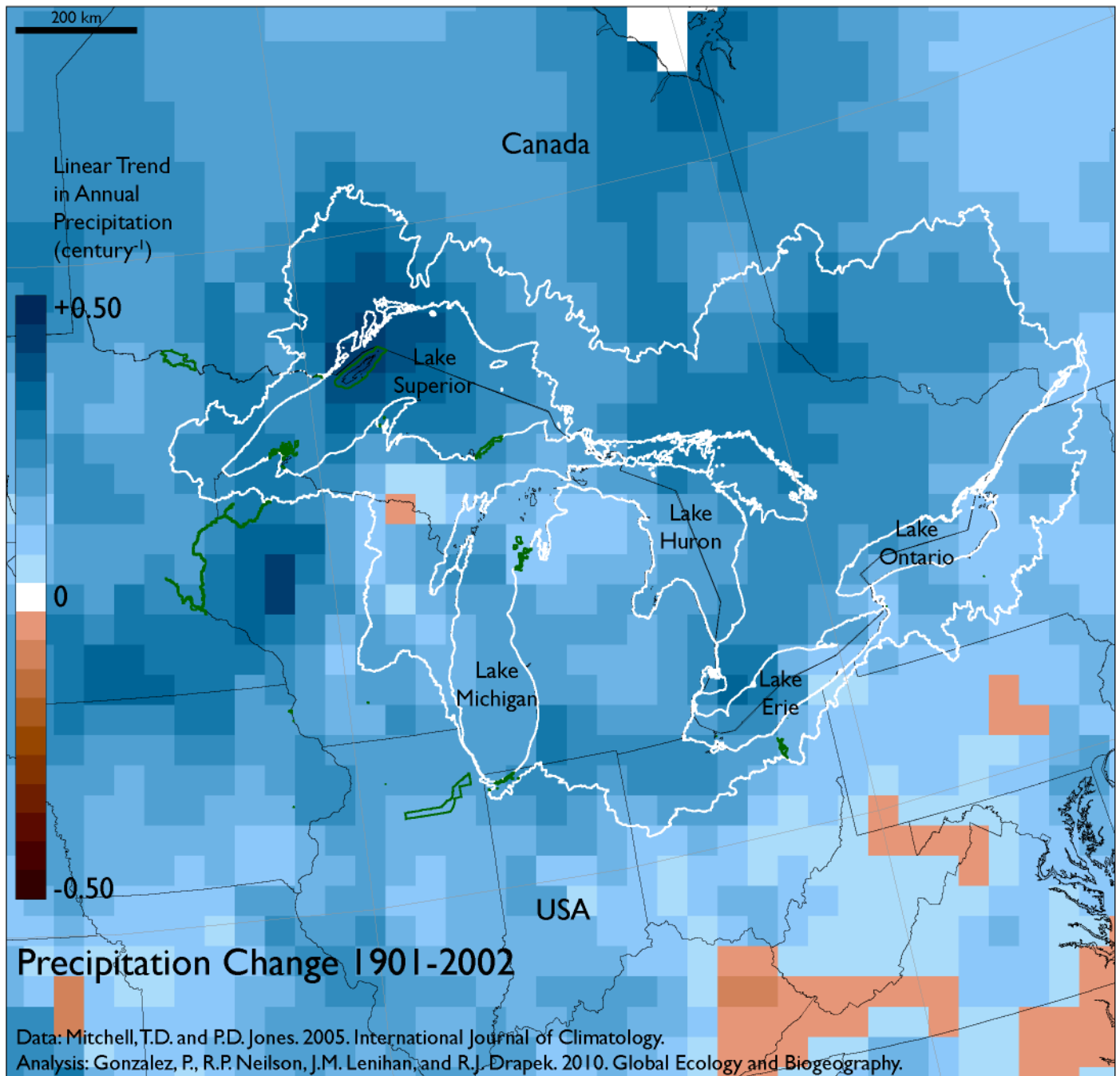


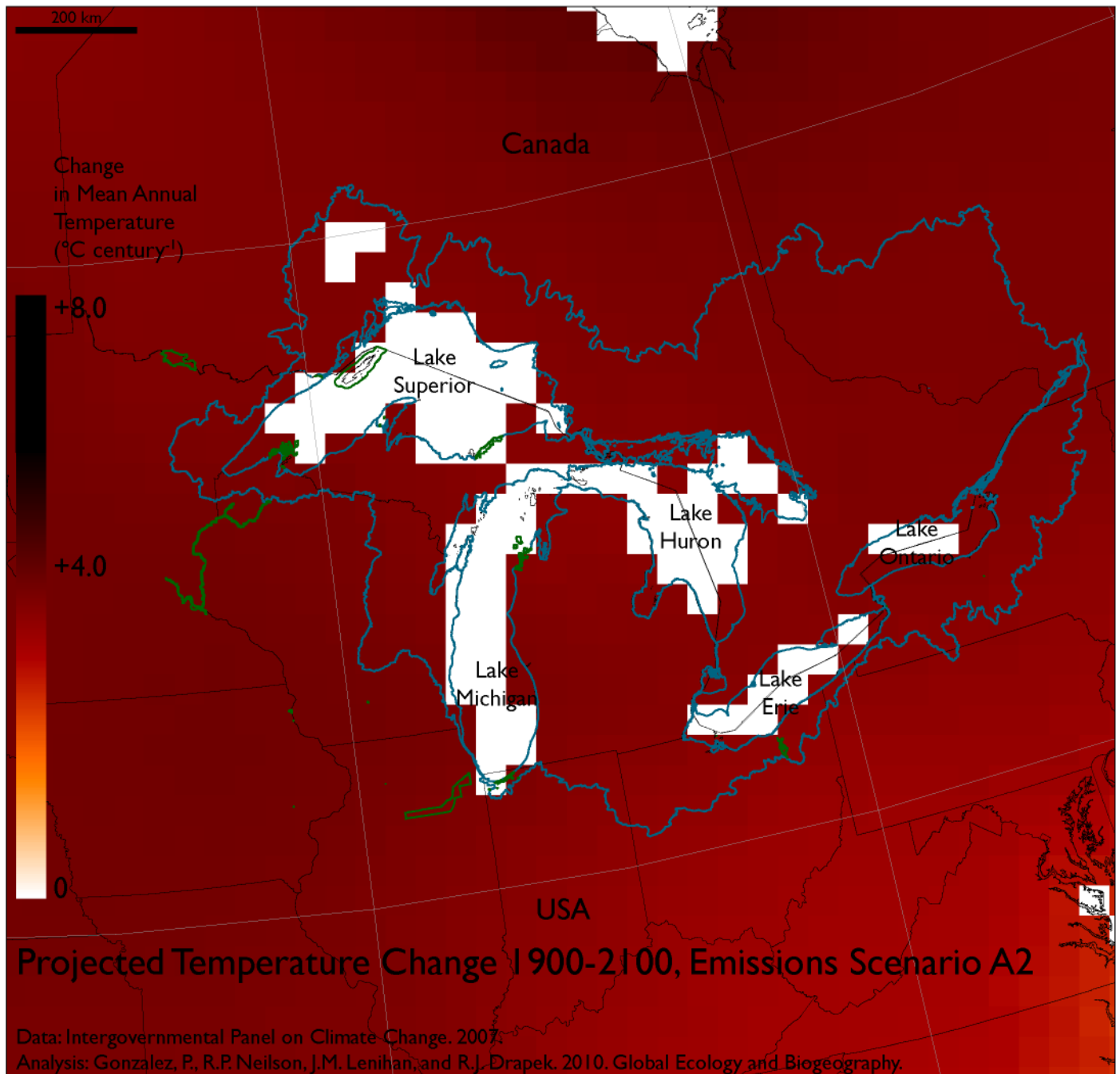
Original diagram from the U.S. Army Corps of Engineers, with modifications

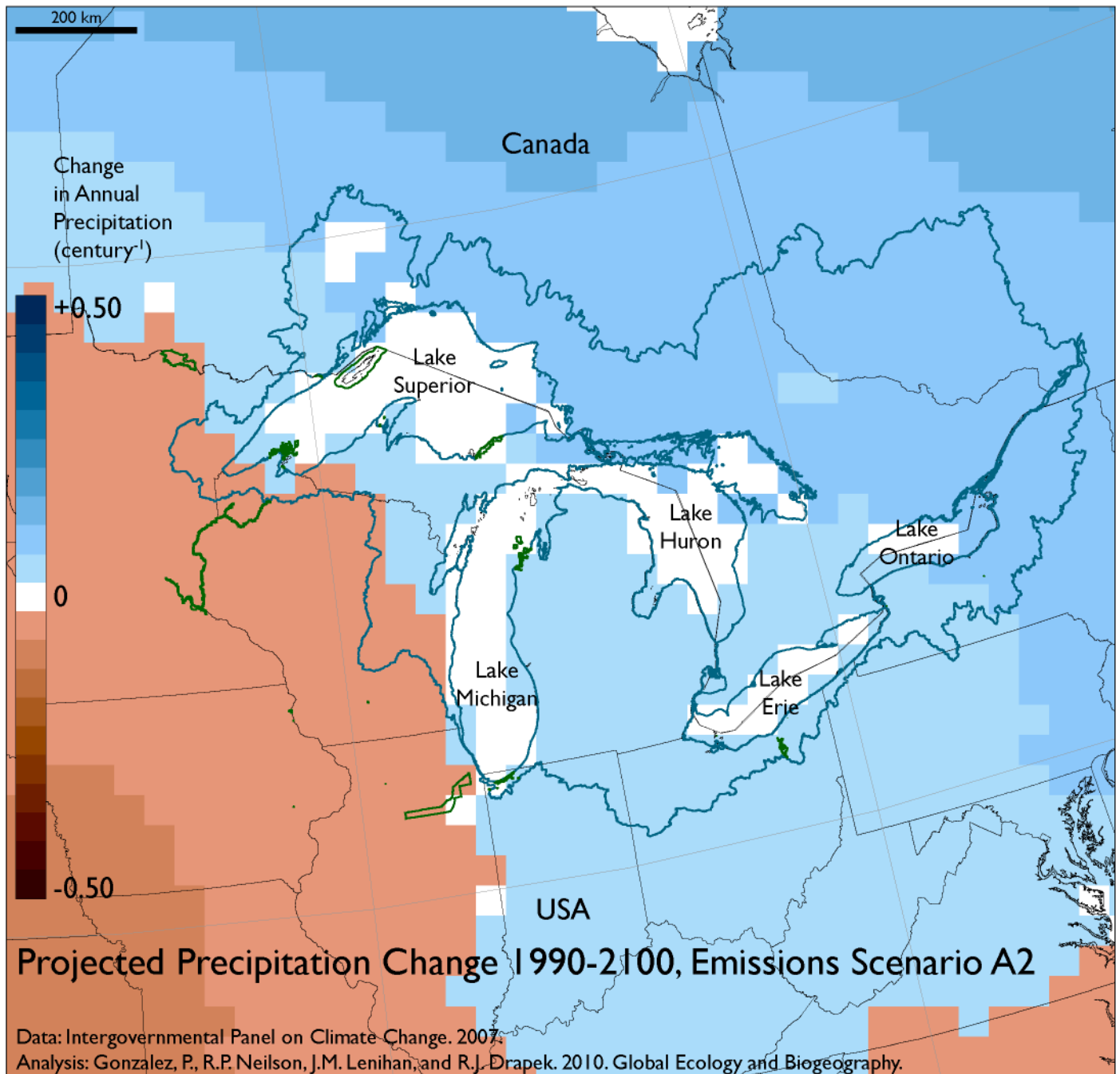
Factors in the Coastal Vulnerability Index (Pendleton et al. 2010),
also called the Change-Potential Index (Pendleton et al. 2007)

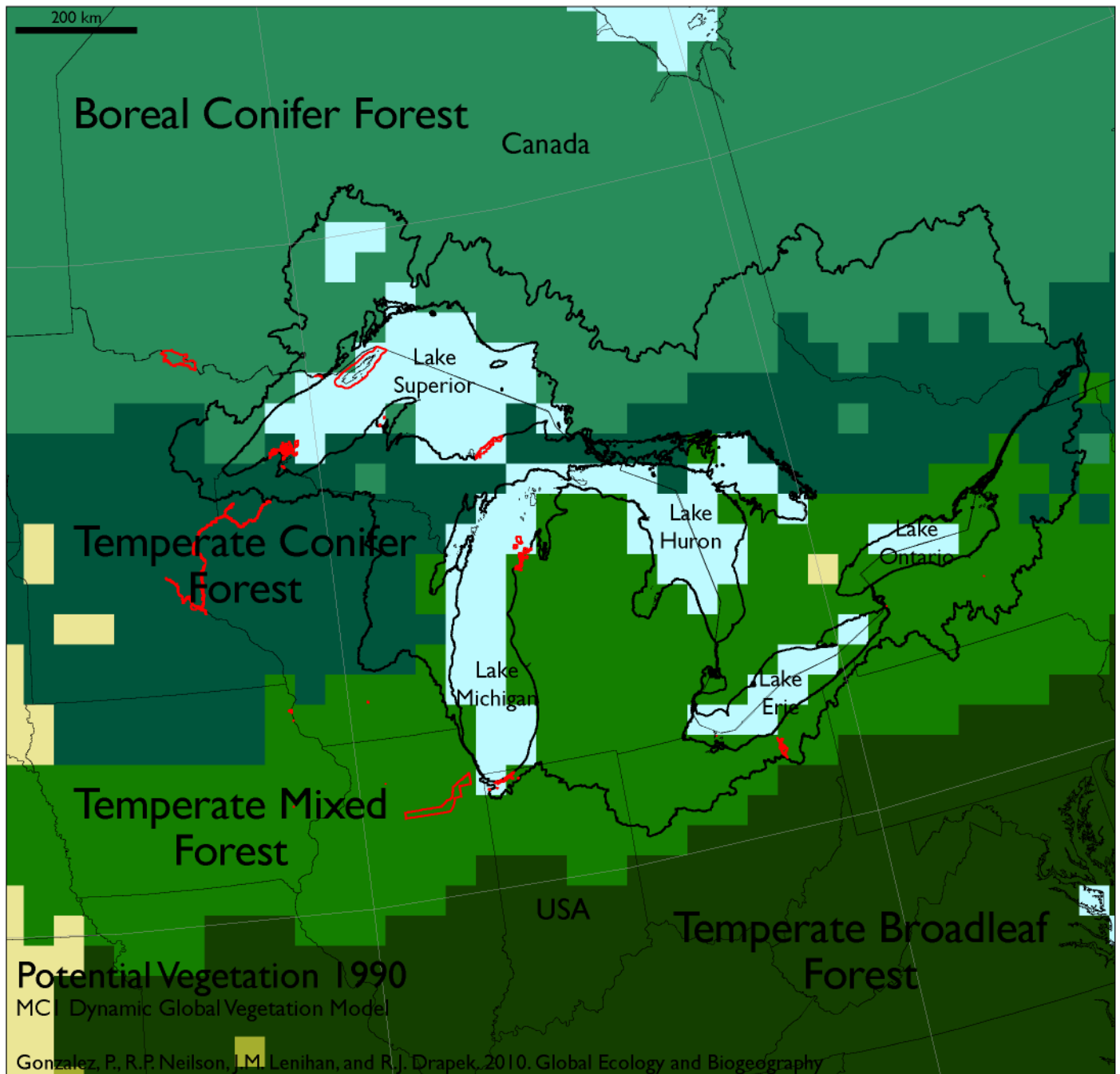
- Geomorphology
- Shoreline change
- Regional coastal slope
- Lake level change rate
- Mean wave height
- Mean tide range
- Mean annual ice cover

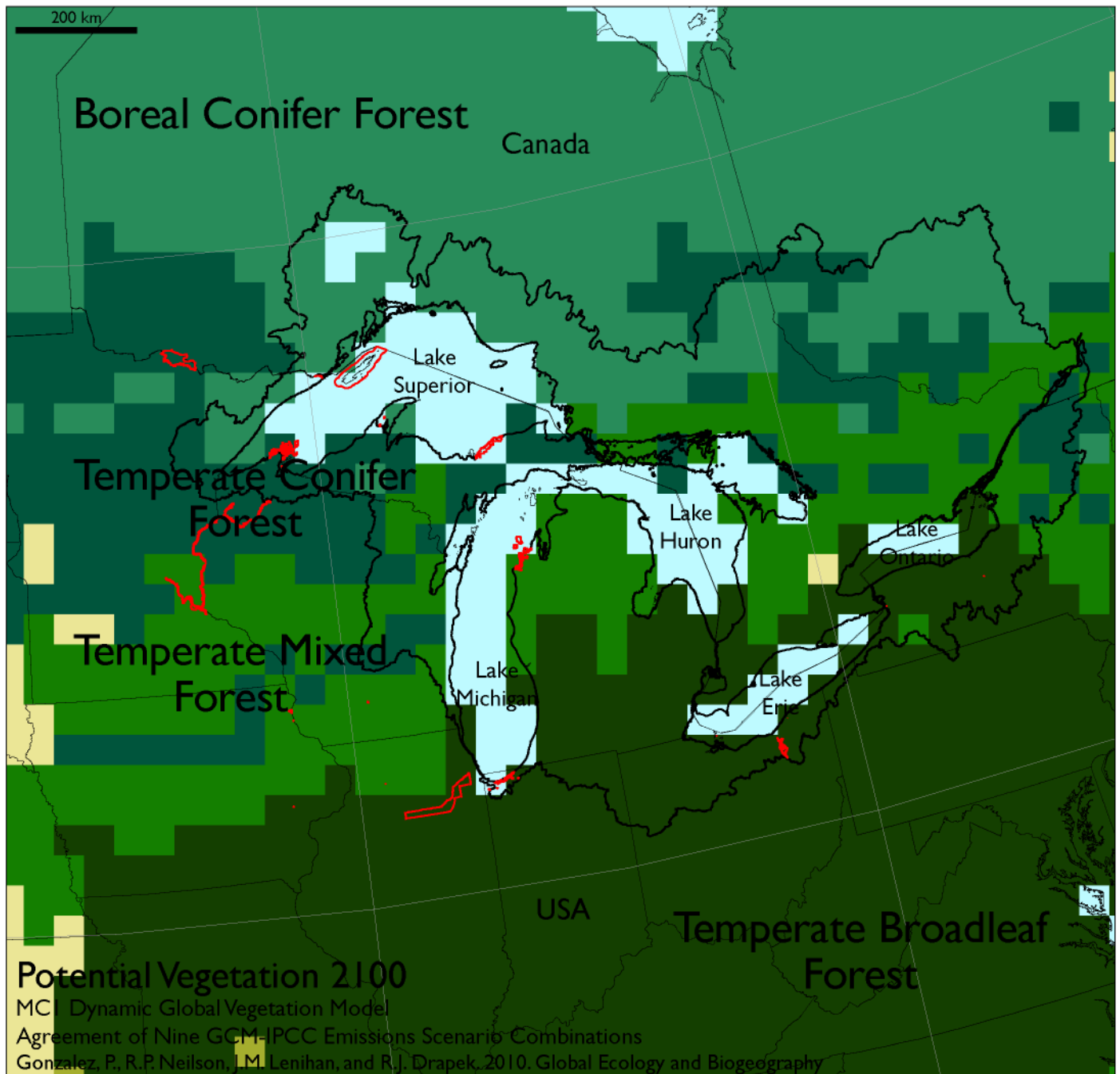


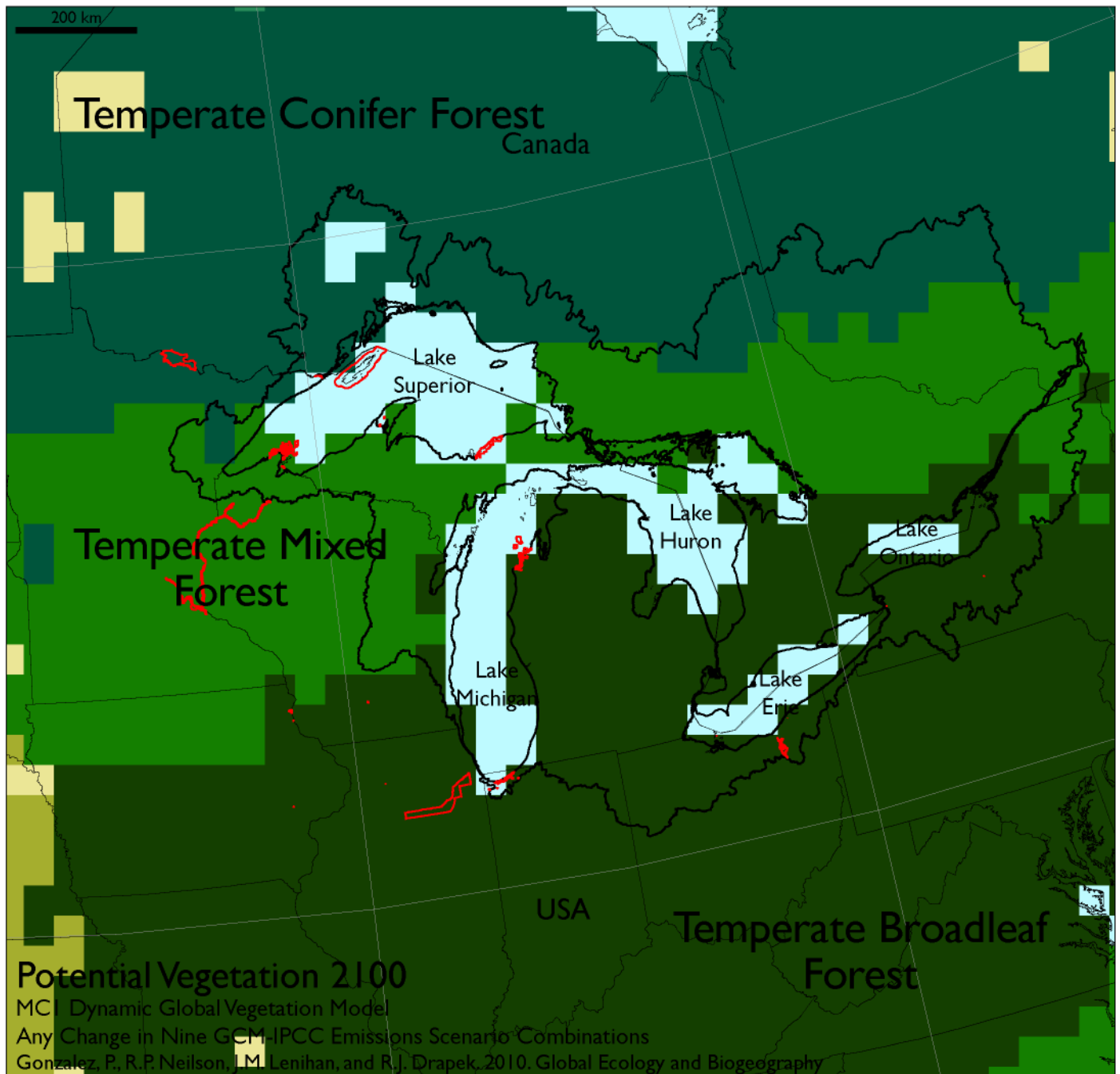


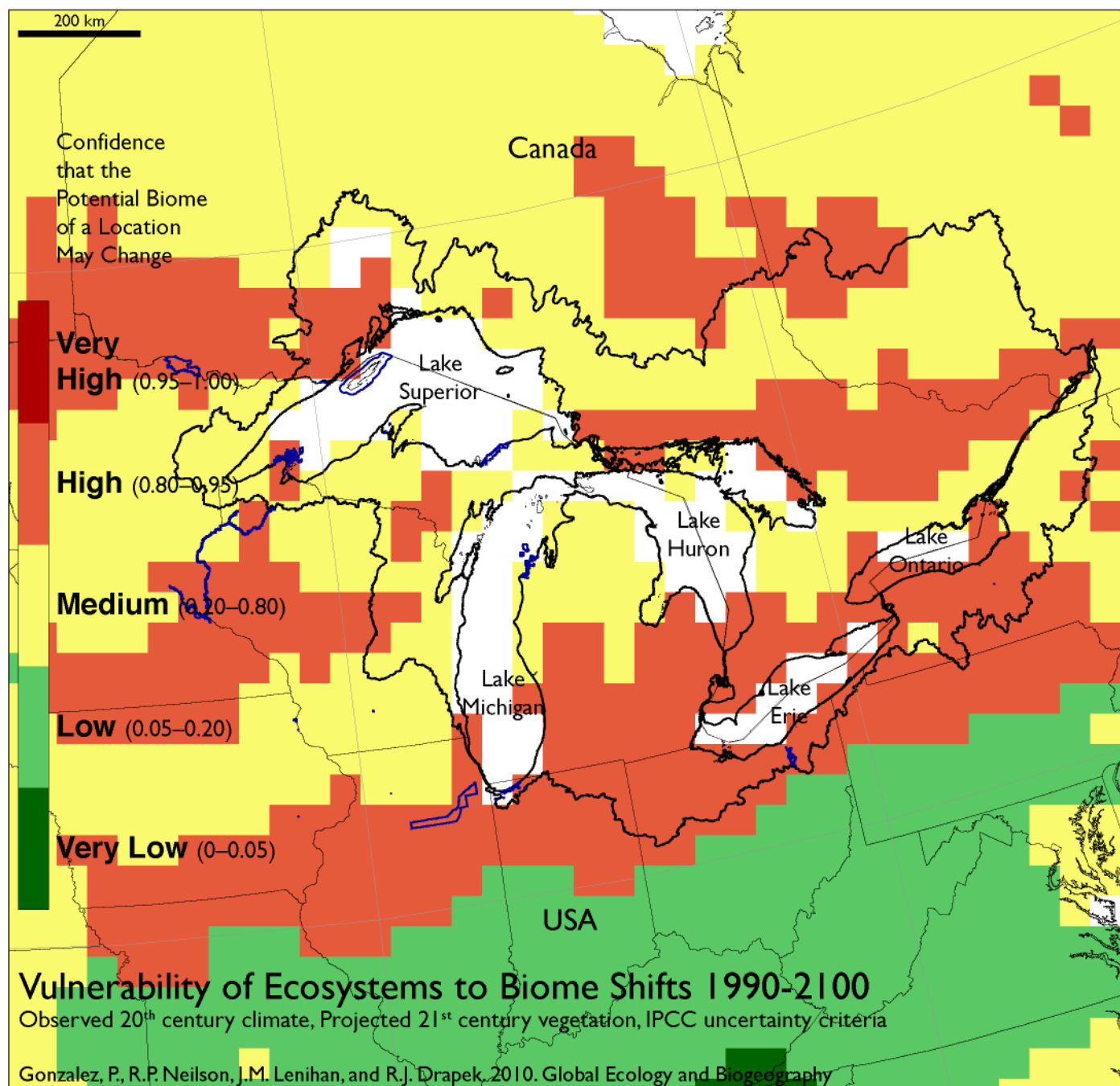




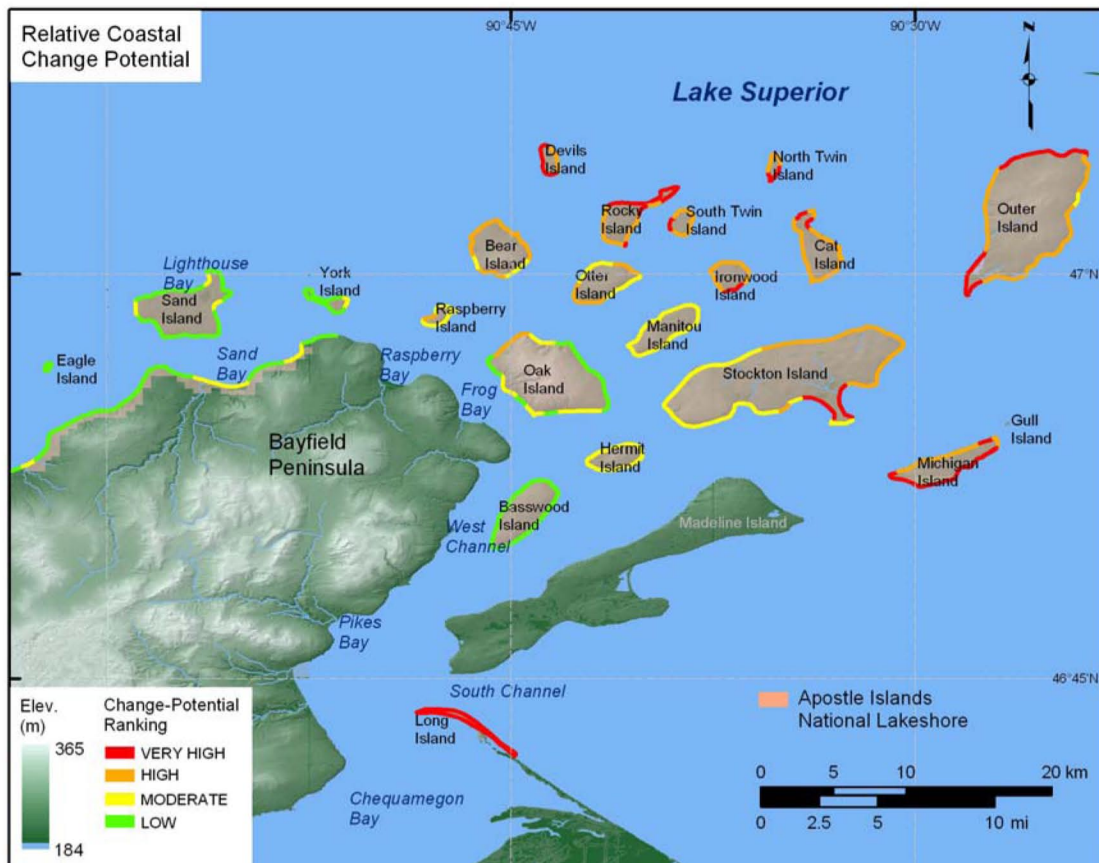






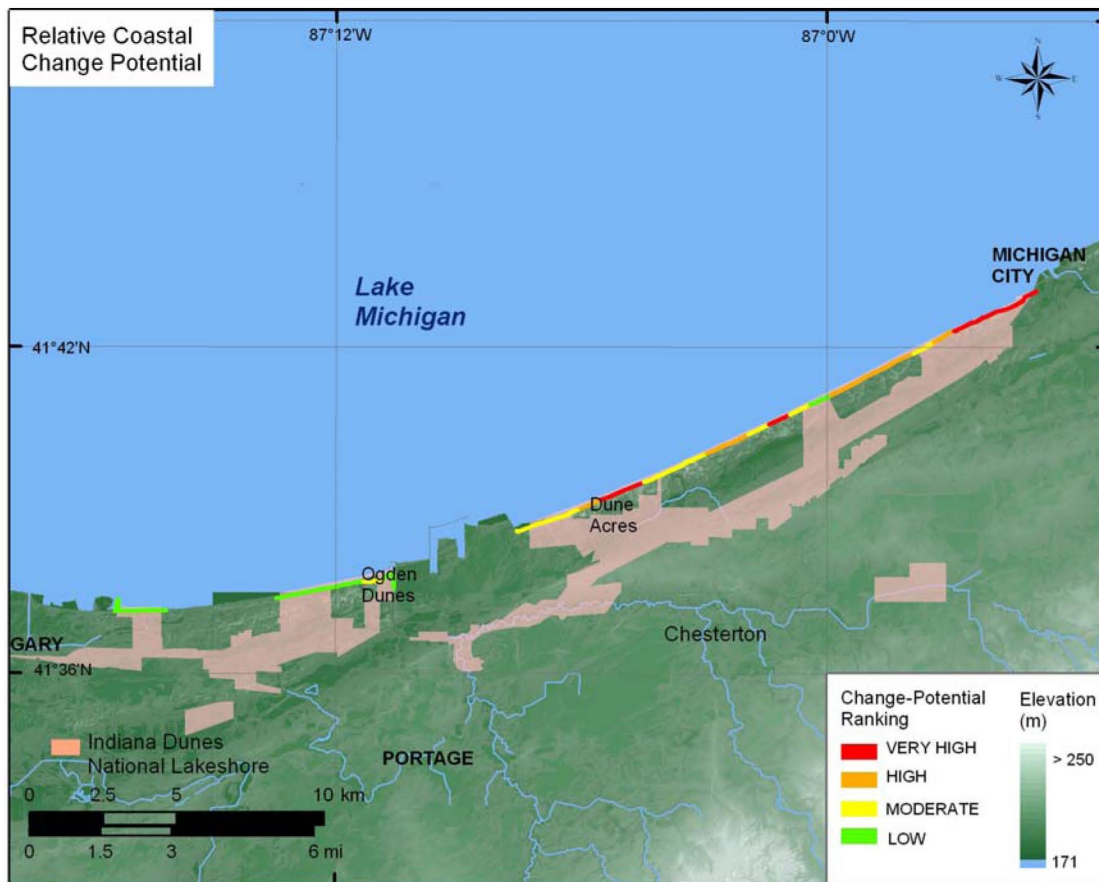


Coastal Change Potential Apostle Islands National Lakeshore



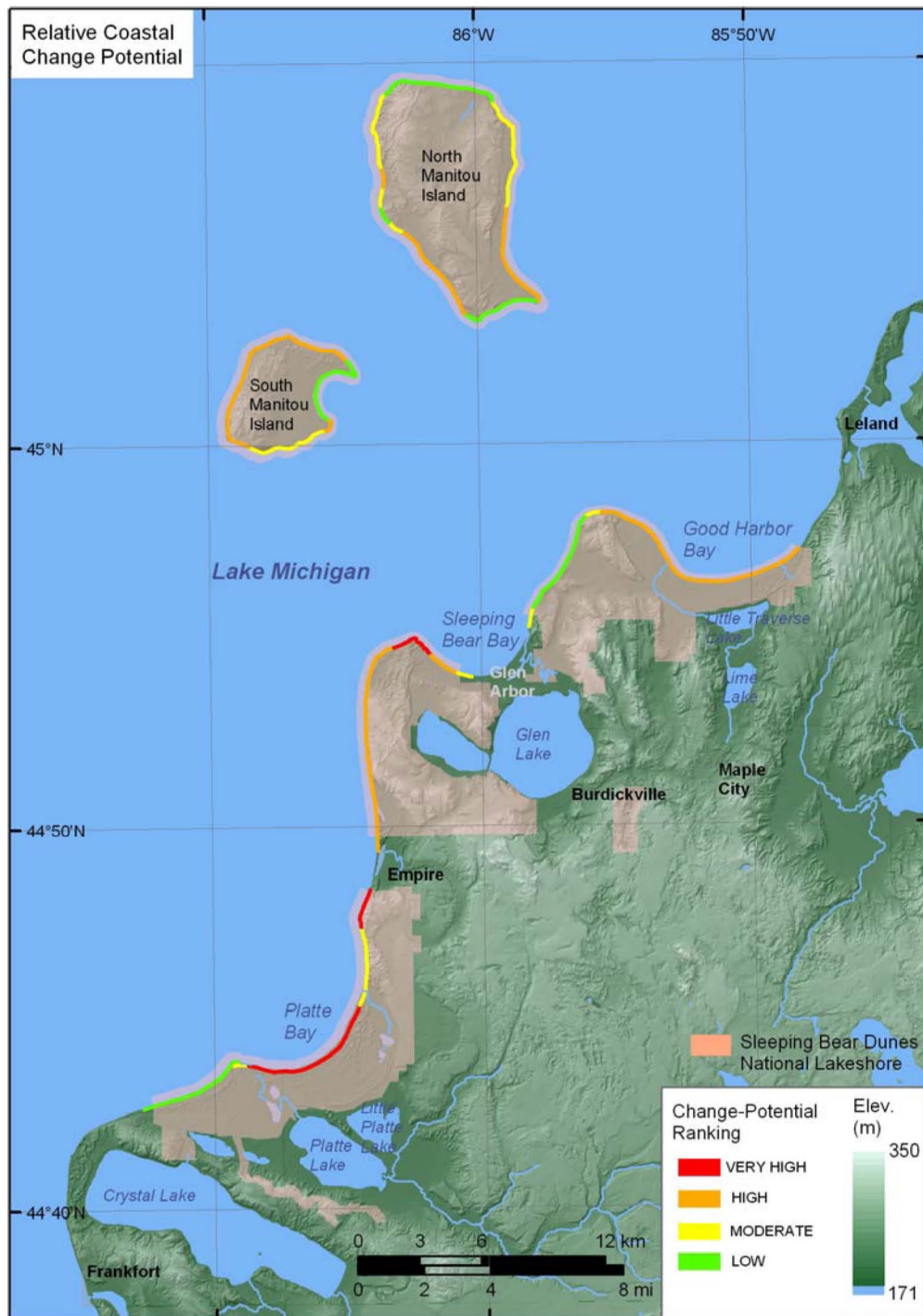
Pendleton et al. 2007

Coastal Change Potential Indiana Dunes National Lakeshore



Pendleton et al. 2007

Coastal Change Potential Sleeping Bear Dunes National Lakeshore



Pendleton et al. 2007

Intergovernmental Panel on Climate Change (IPCC 2007) Treatment of Uncertainty

<u>Confidence Term</u>	<u>Degree of confidence in being correct</u>
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

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